

Suppression of Reflector-Induced Resonance Detuning in a Compact Microstrip Antenna Using Offset Reflector Placement

Narmin H.AL-Zahawi¹ , Haveen Yaseen Hussein AL-Zahawi^{2*} , Saja Mazin Sami³ , and Zainab S. Husamuldeen⁴ 

¹Department of Communication Engineering, University of Diyala, Diyala, Iraq; Email: n.mirza@uodiyala.edu.iq

²Department of Communication Engineering, University of Diyala, Diyala, Iraq; Email: haveeny.al_zahawi@uodiyala.edu.iq

³Department of Electrical power and Machines Engineering, University of Diyala, Diyala, Iraq; Email: S.M.sami@uodiyala.edu.iq

⁴Department of communication Engineering, University of Diyala, Iraq; Email: zainab.salah.eng.comm.@uodiyala.edu.iq

*Correspondence: Haveen Yaseen Hussein AL-Zahawi, haveeny.al_zahawi@uodiyala.edu.iq

ABSTRACT- The impact of reflector symmetry on the frequency stability of the proposed antenna, which employs three elliptical radiating elements printed on a Rogers RT/Duroid 5880 substrate ($30 \times 30 \text{ mm}^2$) and operates around 5.7 GHz, is investigated using different reflector configurations. Full-wave simulations show that a centrally located metallic reflector increases the realized gain from 2.4 to 8.1 dBi; however, the operating resonance shifts downward by approximately 1 GHz, from 5.7 to 4.7 GHz, due to strong symmetric coupling between the antenna current and the image current on the reflector. To mitigate this resonance detuning, an offset-reflector configuration is introduced to provide controlled asymmetric coupling. The simulated offset-reflector configuration preserves operation near 5.7 GHz while providing a realized gain of approximately 3.23 dBi and a radiation efficiency of 94%. Experimental S11 measurements of the unloaded, centered-reflector, and offset-reflector configurations confirm the predicted resonance-detuning and resonance-stabilization trends. Parametric studies are additionally conducted to examine the effects of the elliptical dimensions and substrate thickness on impedance behavior and resonance alignment. The results demonstrate that controlled reflector asymmetry provides a simple, low-complexity strategy for balancing directional enhancement and resonance stability without requiring meta-surfaces, multilayered structures, or other parasitic elements.

Keywords: Compact Microstrip Antenna, Offset Reflector, Resonance Stability, Reflector-Induced Coupling, Directional Radiation Enhancement, Surface Current Distribution, Single-Band Antenna, Impedance Matching.

ARTICLE INFORMATION

Author(s): Narmin H.AL-Zahawi, Haveen Yaseen Hussein AL-Zahawi, Saja Mazin Sami, and Zainab S. Husamuldeen;

Received: 28/05/2026; **Accepted:** 03/09/26; **Published:** 30/09/26;

E- ISSN: 2347-470X;

Paper Id: IJEER 2805B20;

Citation: 10.37391/ijeer.140306

Webpage-link:

<https://ijeer.forexjournal.co.in/archive/volume-14/ijeer-140306.html>



Publisher's Note: FOREX Publication stays neutral with regard to jurisdictional claims in Published maps and institutional affiliations.

1. INTRODUCTION

Reflector-assisted microstrip antennas have attracted considerable research interest for improving the directivity of compact radiating elements in proximity to a reflector surface, owing to their ability to enhance directivity with relatively simple structures and manufacturing processes. However, the interaction between the compact radiators and the neighboring reflective surface still presents a challenge in the design process [1-3]. In addition to its effect on far-field radiation characteristics, a reflector also affects the reactive near-field distribution around the radiator when placed in proximity. This interaction alters the stored electromagnetic energy and can significantly affect the input impedance and operating resonance frequency [4-6]. Near-field resonance effects can be

especially important in compact single-band antennas, where moderate near-field perturbations can significantly affect impedance matching and frequency stability. Different reflector-assisted structures have been reported in the literature that enhance radiation performance using metallic reflectors [7-8], frequency-selective surfaces (FSS) [9-10], electromagnetic bandgap (EBG) structures [11-12], multilayer superstrate structures [13], or metasurfaces [14]. To present the feasibility of low-profile antenna applications with EBG reflector structures, Yang and Rahmat-Samii presented reflection-phase control mechanisms [7]. Meanwhile, Costa et al. analyzed high-impedance FSS structures for the manipulation of electromagnetic fields [8]. Recently, Din et al. [9] proposed an FSS-backed compact antenna as a means for improving gain; Soni proposed a new configuration of phase-gradient metasurfaces to enhance radiation in 5G systems [10]. Reflector-backed compact arrays, AMC-assisted radiators, and higher-order resonant structures have also been examined for improving gain and sidelobe performance [11-14]. However, despite these advances, most studies to date have primarily focused on improving gain, extending bandwidth, enhancing directivity, and/or improving beam-steering performance, rather than examining how reflector-induced coupling affects the resonance stability of reflector-loaded compact antennas. The interaction of the radiator currents with the reflector-induced image currents can be greater when the two are

symmetrically placed relative to one another, causing additional reactive loading near the antenna structure [5-18]. This interaction can undoubtedly impact the operating resonance of electrically compact antennas and is an important part of the overall design process for electrically compact antennas, especially in single-band antenna systems, where stable operating resonance and predictable antenna impedance are essential.

Recent research has used multilayer structures, parasitic elements, periodic loading [9-14], and complex electromagnetic surfaces [19] to reduce high antenna coupling using reflectors. Although these methods have improved radiation performance, the nature of these structures tends to be more difficult to fabricate and more susceptible to electromagnetic interference. Notably, the type of resonator used is not typically cited as a primary design consideration for electromagnetic devices; rather, it tends to be treated as a secondary tuning problem. Various recently reported reflector-loaded antennas have employed metallic reflectors, FSSs, metasurfaces, and RISs to enhance gain and directional radiation patterns [20-25]. In [20], a compact reflector-backed mmWave antenna with a metallic reflector was investigated, and in [21], a reconfigurable antenna with an FSS structure was presented. Furthermore, gain enhancement and directivity improvement using metasurface loading, as well as FSS-assisted sub-6 GHz antennas, have been reported [22-23]. Zarian et al. have presented configurations of FSS with MIMO and reflector structures for beam steering in IoT and V2V applications [24-25]. While resonance improvements were reported by previous researchers, the stability of resonance in these structures and the response of the reflectors used for these applications have not been discussed in detail in most of the published literature. Therefore, the role of reflection symmetry in the resonance stability of compact single-band antennas has not been studied in much detail.

The current research explores the effects of reflector coupling on compact, reflector-loaded, microstrip antennas, focusing on the resonance stability characteristics of compact antennas under different coupling conditions. The majority of prior research on reflector-enhanced antennas has concentrated on maximising realised gain through increased reflector loading. The research presented in this document examines the electromagnetic trade-off between radiation enhancement and resonance stability when using compact single-band resonators as antennas. Full-wave simulation results show that highly symmetric reflector placement can significantly increase realised antenna gain but can also introduce a high amount of excessive reflector-induced reactive near-field coupling, which produces pronounced resonance detuning and instability of the antenna's input impedance. Experimental S11 measurements of the unloaded, centered-reflector, and offset-reflector configurations further support the predicted resonance-detuning and resonance-stabilization behavior. It is shown that symmetry in the placement of a reflector also has a significant effect on electromagnetic parameters that affect the stability of antenna operation. To alleviate the effects of this coupling between the antenna and its reflector, an offset reflector configuration is

proposed. This layout creates controlled asymmetry used to limit excessive coupling between the radiator and reflector via image-current interaction and therefore limit resonance displacement while providing directionality and high efficiency in radiated power, without the use of metasurfaces, multilayer superstrates, or parasitic structures.

The remainder of the paper is organized as follows: *Section 2* presents the antenna evolution procedure and design methodology. *Section 3* discusses the investigated reflector configurations and parametric analyses relating to these configurations. *Section 4* presents the simulated electromagnetic characteristics, including reflection coefficient behavior, surface current distributions, radiation characteristics, and Monte Carlo tolerance analysis. Finally, *Section 5* presents the conclusions of this research.

2. ANTENNA CONFIGURATION AND DESIGN METHODOLOGY

2.1. Antenna Geometry

Figure 1 illustrates the geometry of the proposed antenna, which is built on a Rogers RT/Duroid 5880 substrate (with a 0.5 mm thickness and 2.2 relative permittivity) and has an overall size of 30×30 mm². Thus, this antenna is sufficiently compact to be used at frequencies below 6 GHz. The radiating element comprises three metallic elliptical elements printed on the top of the substrate, with a 50 Ω microstrip feedline acting as the excitation source. The elliptical configuration was chosen since it provides a smooth current distribution and stable impedance characteristics within the operating frequency range of the antenna (*i.e.*, below 6 GHz). Additionally, a partial ground plane printed on the rear side of the substrate was used to improve the antenna impedance response. A metallic reflector was positioned behind the antenna structure with an air separation between the two conductive surfaces. A parametric analysis of the influence of reflector position and spacing from the antenna was conducted and is discussed in this paper. The optimised dimensions for the proposed antenna are presented in *table 1*.

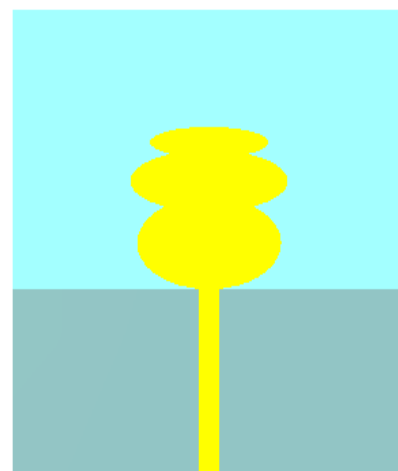


Figure 1. Top view of the antenna

Table 1. Geometrical Parameters

Parameter	Value (mm)
Length and width of the substrate	30
Width of the ground	12
Feed line length	12
Width feed line	1.5
Upper ellipse semi-major (a1) / semi-minor axes (b1)	4 / 1
Middle ellipse semi-major (a2)/ semi-minor axes (b2)	6 / 2
Lower ellipse semi-major (a3) / semi-minor axes(b3)	5.5 / 3
Reflector width	40
Reflector length	80
Antenna-to-reflector air gap, d_r	13.5
Reflector Offset	5

2.2. Design Evolution Procedure

The geometrical form of the antenna was developed through iterations to achieve the desired impedance characteristics over the operating frequency range. The evolution of the antenna geometry is shown in *figure 2*, and the antenna reflection coefficient responses are shown in *figure 3*. The first antenna design used a single elliptical radiator directly connected to the microstrip feedline, as shown in *figure 2(a)*. The S11 response shown in *figure 3* indicated that the structure could produce a resonance at the operating frequency, but the impedance matching was not sufficiently strong, resulting in a shallow resonance. The short effective current path and the limited surface current distribution resulting from a single-radiator configuration are the primary causes of this behaviour. A close relationship exists between the resonant behaviour of the radiator and its effective electrical length, which can be approximated by

$$f_r = \frac{c}{2L_{eff} \sqrt{\epsilon_{eff}}} \quad (1)$$

Resonance frequency f_r , Radiator effective electrical length L_{eff} , Speed of light (c) and Effective dielectric constant ϵ_{eff} . Thus, altering the geometry of the radiator will directly change both the path distribution and therefore its resonance characteristics. Another elliptical section has been added to enhance the electromagnetic coupling within the radiator seen in *figure 2 (b)*. This modified radiator provides improved electrical length and the current distribution in the vertical direction. This will provide an improved impedance response and therefore a stronger resonant response as compared to the original setup. Finally, the addition of the third elliptical portion seen in *figure 2(c)* is added to the model. By introducing this new area to the antenna (as a separate section from the radiating structure), the surface current is displaced throughout the total area, thus allowing for a more concentrated resonant response at the required operating frequency. As demonstrated in *figure 3*, the triple-ellipse configuration exhibited much better impedance-matching ability with a much lower reflection coefficient than any previous configuration. An increase in the effective radiating surface area may account for this difference

in the antenna's impedance response. The increase in effective radiating area stabilizes the electromagnetic coupling between the radiator sections and increases the electric and magnetic energy stored in the resonant structure (the region around the radiator). These results indicate that the addition of the elliptical portion(s) of the configuration has a significant effect on the effective current path of the antenna and its resonant characteristics. The triple-ellipse configuration, therefore, was selected for further parametric studies and reflector analyses based on these results.

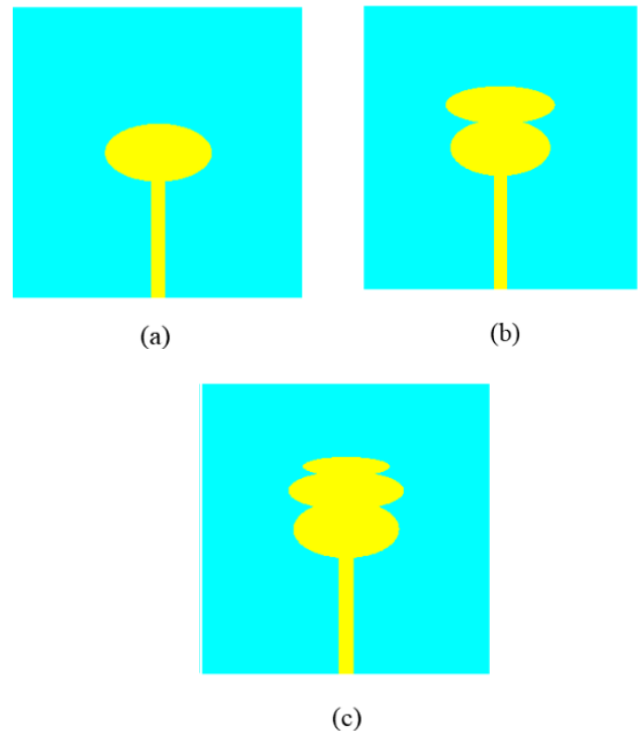


Figure 2. Geometrical evolution of the proposed antenna radiator: (a) single-ellipse radiator, (b) dual-ellipse radiator, and (c) triple-ellipse radiator

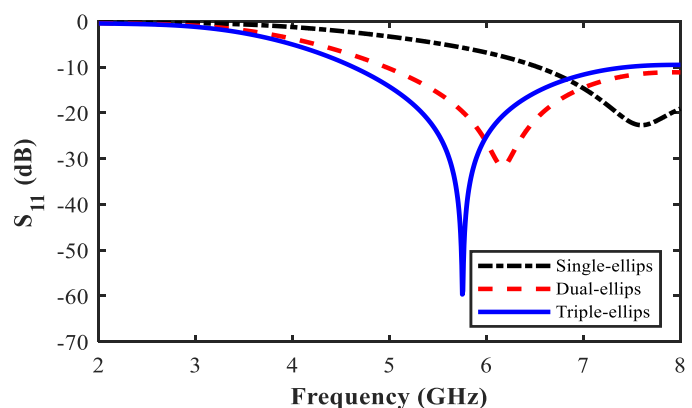


Figure 3. Simulated reflection coefficient responses for different antenna evolution stages

2.3. Simulation Setup

Full-wave electromagnetic simulations were performed using CST Studio Suite with the time-domain solver over the frequency range of 2–8 GHz. The antenna was modeled on a

0.5-mm-thick Rogers RT5880 substrate with a relative permittivity of $\epsilon_r=2.2$ and relative permeability of $\mu_r=1$. In the implemented model, the substrate was treated as loss-free. Open (add space) boundary conditions were applied in all six directions to emulate free-space radiation. The antenna was excited using a single waveguide port located at the end of the microstrip feed line, with one propagating mode. A hexahedral mesh was employed, and the time-domain solver accuracy was set to -40 dB. The radiator, feed line, and ground plane were modeled as annealed copper with an electrical conductivity of 5.8×10^7 S/m and a thickness of 0.035 mm. The metallic reflector was modeled as a perfect electric conductor (PEC).

2.4. Semi-Axis Optimization

After selecting the triple-ellipse radiator configuration, the next step was to study semi-major-axis dimensions suitable for tuning the resonant position and impedance-matching behavior. Two main geometrical parameters were analyzed: the semi-major axes of the upper and lower elliptical elements, as shown in figure 4.

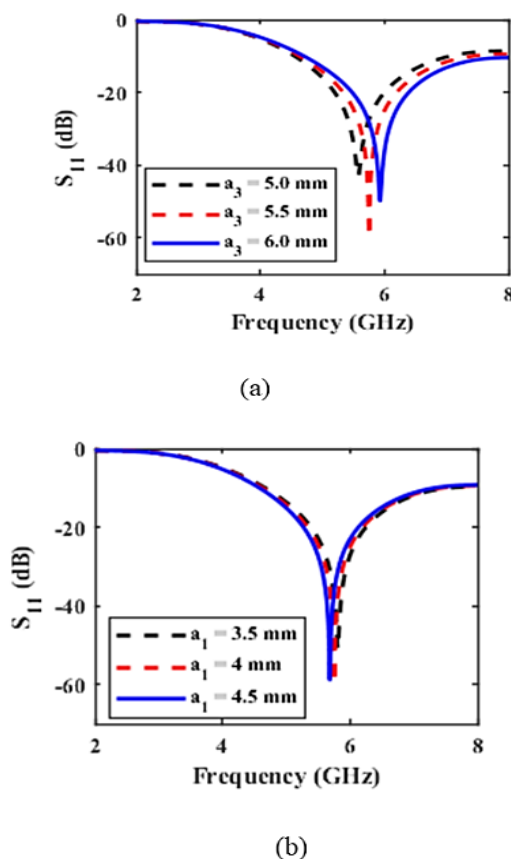


Figure 4. Effect of radiator semi-major-axis variation on the simulated reflection coefficient: (a) lower ellipse and (b) upper ellipse

The semi-major axis of the lower ellipse varies from 5 mm to 6 mm, as depicted in figure 4(a). A small change in radius shifts the resonance toward a higher-frequency region and affects the matching depth. This behavior clearly indicates that the lower elliptical section affects the current distribution and the transition between the stacked elliptical elements and the impedance. Among all tested values, lower-ellipse semi-major

axis of 5.5 mm produced the deepest resonant response, indicating that the impedance match was optimal for the desired operating band. The influence of the upper radius is shown in figure 4(b). The frequency variation due to changes in the upper radius was smaller than that of the lower radius, while the resonance depth was still significantly influenced. When considering the coupling between the feedline and the radiator or the modification of the electrical length, it is clear that the upper elliptical section has a greater impact on coupling. The optimized upper-ellipse semi-major axis is 4 mm, which gives the best impedance-matching response among all the cases studied. The results from the semi-major-axis optimization show that the resonance characteristics of the radiator, with respect to the effective current path and the electrical behavior of the elliptical sections, can be controlled. As a result, the final chosen semi-major-axis dimensions were 5.5 mm for the lower ellipse and 4 mm for the upper ellipse for further study of the reflector.

2.5. Substrate Thickness Investigation

To determine the effect of substrate thickness on the impedance response of the antenna, the radiator dimensions were optimized and two different substrate thicknesses were tested. The analysis of the resonant depth and impedance matching clearly shows, as also demonstrated by the S_{11} results in figure 5, that both performance characteristics depend strongly on substrate thickness. The thinner substrate (0.5 mm) gives a higher resonant frequency and better matching near the desired operating frequency, primarily because it confines the electromagnetic field and reduces surface-wave excitation. The opposite is true for thicker substrates, where larger radiating fields develop around the radiator, leading to poor current confinement and poor impedance matching. Based on these results, the substrate thickness chosen for the subsequent reflector-loading investigation is 0.5 mm.

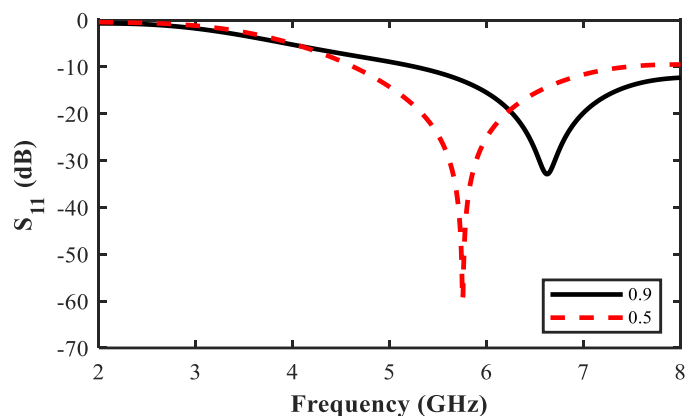


Figure 5. Simulated reflection coefficient responses for different substrate thickness values

3. RESULTS AND DISCUSSION

3.1. Reflection Coefficient Analysis

The investigated reflector configurations are shown in figure 6, including both the conventional centered reflector configuration and the proposed offset reflector configuration. The metallic reflector has dimensions of 80×40 mm² and is positioned at a normal separation of 13.5 mm from the antenna. The reflector

offset, d_{off} , is defined as the center-to-center displacement between the antenna and reflector along the y-axis. Accordingly, $d_{\text{off}} = 0$ mm represents the centered configuration, whereas the optimized asymmetric configuration corresponds to $d_{\text{off}} = -5$ mm (5-mm absolute offset). The corresponding simulated reflection coefficient responses are presented in figure 7. The results demonstrate that the inclusion of a nearby metallic reflector substantially modifies the resonant behaviour of the compact radiator due to the additional electromagnetic interaction between the radiator currents and the reflector-induced image currents.

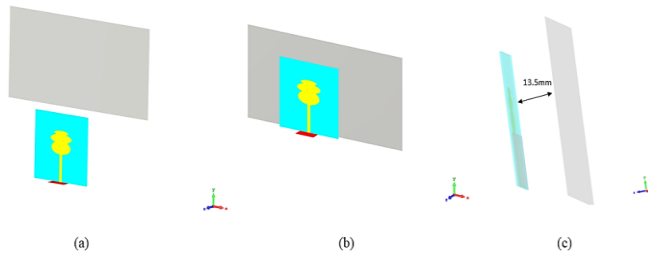


Figure 6. Reflector configurations of the proposed antenna: (a) offset reflector, (b) centered reflector, and (c) side view illustrating the fixed 13.5-mm antenna-to-reflector air gap

The results demonstrate that the inclusion of a nearby metallic reflector substantially modifies the resonant behavior of the compact radiator due to electromagnetic interaction between the radiator currents and the reflector-induced image currents. Quantitatively, the centered-reflector configuration shifts the resonance from approximately 5.7 GHz to 4.7 GHz, corresponding to a downward displacement of approximately 1.0 GHz. In contrast, the optimized offset configuration maintains the resonance close to 5.7 GHz. This substantial reduction in resonance displacement indicates that asymmetric reflector placement reduces the effective reflector-induced reactive perturbation experienced by the radiator.

Under centered reflector loading, the stronger symmetric interaction perturbs the reactive near-field distribution surrounding the compact resonator and modifies its effective electrical length, as indicated in eq. (1), resulting in the observed downward resonance shift. Although the centered reflector provides substantial simulated gain enhancement, this occurs at the expense of resonance stability.

The proposed asymmetric offset-reflector configuration controls this interaction through reflector placement. The lateral displacement redistributes the induced current distribution relative to the radiator, reducing the effective reactive perturbation and thereby maintaining the resonance closer to the intended operating frequency while preserving useful directional radiation enhancement and high simulated radiation efficiency.

These results demonstrate that reflector symmetry is an important design parameter governing the resonance stability of compact reflector-loaded antennas. Therefore, the lower simulated gain of the offset configuration relative to the centered configuration represents a trade-off for improved

resonance preservation and more predictable impedance behavior.

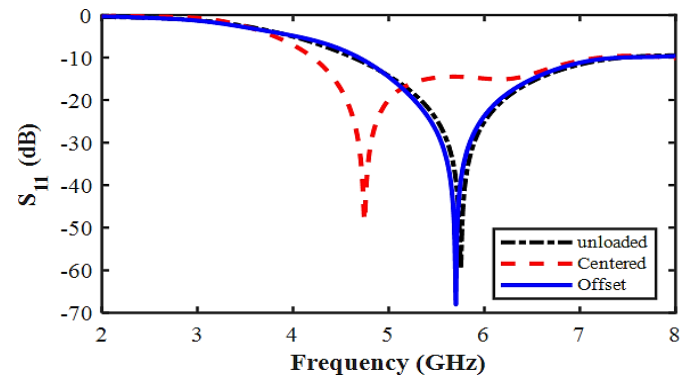


Figure 7. Simulated reflection coefficient responses for the unloaded, centered reflector, and offset reflector configurations

3.2. Reflector Offset Investigation

The reflector offset, d_{off} , is defined as the center-to-center displacement between the antenna and the reflector along the y-axis. Accordingly, $d_{\text{off}} = 0$ mm represents the geometrically centered configuration, while the optimized asymmetric configuration corresponds to $d_{\text{off}} = -5$ mm (5-mm absolute offset). The reflector-position sweep in fig. 8 was referenced to the antenna center, using $d_{\text{off}} = -25, -15, -5, +5$, and $+15$ mm.

The simulated S_{11} responses in fig. 8 demonstrate that the antenna resonance is sensitive to reflector alignment. As the reflector approaches a more symmetric alignment with the radiator, stronger interaction between the radiator current and the induced image current modifies the reactive loading and produces a more pronounced resonance shift. Conversely, asymmetric reflector placement reduces this interaction and improves resonance stability. Among the investigated positions, the optimized $d_{\text{off}} = -5$ mm configuration provides the most favorable combination of resonance preservation and impedance matching near the intended operating frequency. Further displacement from this position results in reduced resonance depth and slightly degraded impedance matching. These results demonstrate that reflector offset is an important design parameter for controlling reflector-induced coupling and maintaining resonance stability.

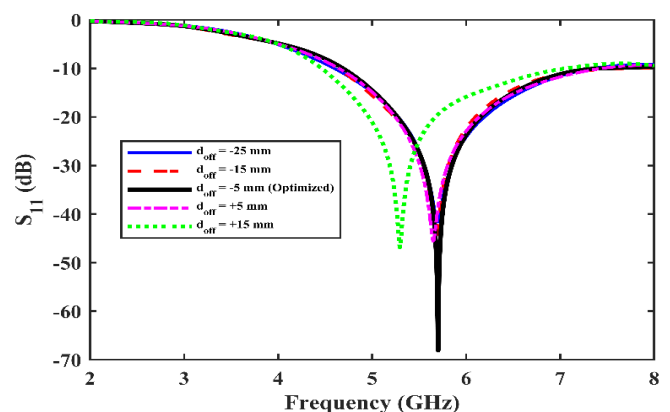


Figure 8. Simulated S_{11} responses for different center-referenced reflector offsets

3.3. Air-Gap Investigation

Figure 9 illustrates the air-gap spacing between the antenna and the PEC reflector. The air-gap spacing, d_r , is defined as the normal separation between the antenna/substrate plane and the facing surface of the reflector. The results indicate that variations in this spacing effect both the impedance response and resonance characteristics of the antenna. The air gap also influences the phase relationship between the directly radiated field and the reflector-assisted field. Considering the round-trip propagation path between the antenna and reflector, the associated phase difference can be qualitatively expressed as

$$\Delta\phi = 2\beta d_r + \phi_r \quad (2)$$

where $\beta = 2\pi f/c$ is the free-space propagation constant, d_r is the antenna-to-reflector air gap, and ϕ_r is the reflection phase of the reflector. Since the reflector is modeled as a PEC, the reflection phase is approximated as $\phi_r = \pi$ (180°). The term $2\beta d_r$ accounts for the round-trip propagation between the antenna and reflector. Thus, changing d_r modifies the phase relationship between the directly radiated and reflector-assisted fields and consequently changes their constructive or destructive interaction. Equation (2) is used here as a qualitative interpretation of the spacing-dependent behavior rather than as an exact analytical prediction of the optimum spacing.

Throughout the investigated cases, varying the air-gap spacing produced changes in the resonance depth and resonance position, as shown in figure 9. The full-wave parametric sweep identified $d_r = 13.5$ mm as the selected spacing, providing the deepest resonance and best impedance-matching response among the investigated values. Smaller and larger air gaps produced less favorable interaction between the antenna and reflector and consequently reduced the resonance depth. Therefore, the 13.5-mm spacing used in the subsequent reflector configurations was selected from the simulated parametric results rather than directly predicted by the simplified phase relation in eq. (2).

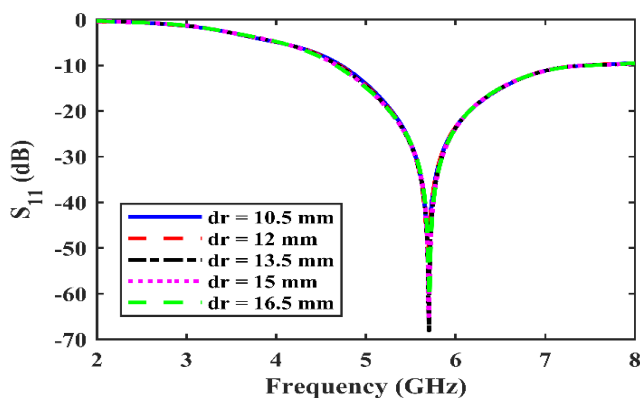


Figure 9. Simulated S11 responses for different air-gap spacing values

3.4. Surface Current Distribution Analysis

The simulated surface-current distributions for the investigated reflector configurations are shown in figure 10. These distributions provide qualitative physical insight into the

resonance perturbation mechanism associated with reflector loading in the compact radiator. For the centered-reflector configuration shown in fig. 10(a), a pronounced and symmetric current concentration is observed in the region of the reflector aligned with the radiator. This distribution indicates stronger reflector-induced reactive interaction between the radiator currents and the corresponding image currents on the metallic reflector, resulting in a greater perturbation of the reactive near-field environment surrounding the radiator. This interpretation is consistent with the S11 results, where the centered reflector shifts the resonance from approximately 5.7 GHz to 4.7 GHz, corresponding to a downward resonance displacement of approximately 1.0 GHz.

In contrast, the optimized offset-reflector configuration shown in fig. 10(b) produces a less symmetric distribution of the induced currents relative to the radiator. The reflector displacement changes the spatial distribution of the induced currents and reduces the effective reactive perturbation experienced by the radiator. Consequently, the antenna resonance remains close to the intended 5.7 GHz operating region, as observed in the corresponding S11 response. The surface-current distributions are therefore used here as qualitative support for the physical interpretation of the resonance behavior rather than as a quantitative measure of mutual coupling. Together with the quantitatively observed resonance displacement, these results indicate that controlled reflector asymmetry reduces reflector-induced resonance perturbation and improves resonance stability.

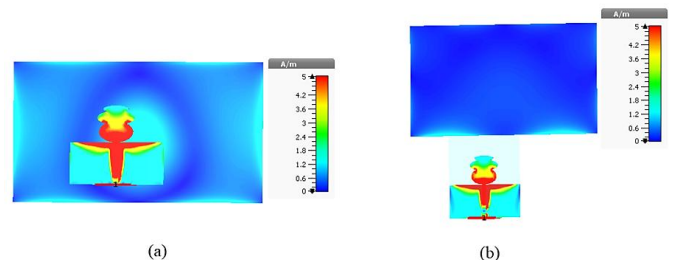


Figure 10. Simulated surface-current distributions for (a) centered reflector at 4.7 GHz and (b) optimized offset reflector at 5.7 GHz, using the same current scale (0–5 A/m)

3.5. Radiation Characteristics

The simulated radiation patterns of each proposed antenna configuration are shown in figures 11 and 12, whereas the electromagnetic performance characteristics of each configuration can be found in table 2. The unloaded configuration produces relatively broad radiation characteristics and has a moderate realized gain of 2.4 dBi because the absence of a reflecting surface does not allow the redirection of backward radiation. This results in the radiated fields being more spatially distributed, which causes stable resonance behavior, predictable impedance characteristics, with a radiation efficiency of 94.39% at the 5.7 GHz resonance. The impedance bandwidth reported in Table 2 is determined using the -10 -dB reflection-coefficient criterion ($S_{11} \leq -10$ dB) and is calculated as $BW = f_H - f_L$, where f_L and f_H denote the lower and upper -10 -dB frequency limits, respectively.

Table 2. Electromagnetic performance trade-off analysis of the investigated reflector configuration

Configuration	Resonance frequency (GHz)	Realized Gain dBi	Radiation Efficiency (%)	VSWR	Bandwidth (GHz)	Coupling condition	Resonance stability	Resonance detuning
Unloaded-Antenna	5.7	2.4	94.39%	Below 2	2.66	Weak coupling	Stable	Negligible
Centered Reflector	4.7	8.1	92.81%	Below 2	2.86	Strong symmetric coupling	Unstable	Severe
Offset Reflector	5.7	3.23	94.57%	Below 2	2.56	Controlled asymmetric coupling	Stable	Suppressed

The centered reflector configuration provided a much greater amount of directional radiation enhancement, resulting in a realized gain of approximately 8.1 dBi. Quantitatively, at 4.7 GHz, the centered-reflector configuration exhibits a peak realized gain of 8.11 dBi with a main-beam direction of -2° , a 3-dB half-power beamwidth (HPBW) of 67.7° , and a front-to-back (F/B) ratio of 13.52 dB. This behavior is primarily due to the strong constructive interaction that occurs between the direct radiator fields and the reflector-induced image currents, which increase field confinement and also concentrate the forward radiation. At its shifted resonance of 4.7 GHz, the centered configuration exhibits a radiation efficiency of 92.81%. The E-plane and H-plane responses also show highly symmetric radiation behavior due to the strong electromagnetic interaction that occurs between the radiator and the reflector surface.

The results from the experiments demonstrate that the strong symmetric reflector loading has simultaneously intensified the reactive near-field coupling surrounding the compact resonator, which has substantially perturbed the distributed reactive electromagnetic fields responsible for maintaining stable resonance operation and caused significant displacement of the resonance towards lower frequencies, as determined from the reflection coefficient and surface current analyses. While the centered reflector configuration provided the highest realized gain and the widest impedance bandwidth, this configuration resulted in a substantial destabilization of the operating resonance condition.

The large difference in realized gain among the three configurations should not be interpreted as a corresponding difference in radiation efficiency. The reflector primarily modifies the spatial redistribution and directivity of the radiated fields, whereas radiation efficiency represents the fraction of accepted power that is radiated rather than dissipated. Consequently, substantial changes in realized gain can occur while the radiation efficiencies remain relatively high. For completeness, the corresponding total efficiencies at the

respective resonances are 94.38%, 92.75%, and 94.57% for the unloaded, centered-reflector, and offset-reflector configurations, respectively.

In contrast, a more controlled electromagnetic response was established through asymmetric reflector loading. Therefore, the electromagnetic response produced by the lateral displacement of the reflector suppressed excessive image current interaction beneath the radiator and reduced the perturbation of the resonant current paths. A reduction in the strength of perturbations along resonant current paths allowed the antenna to maintain stable resonance at the desired 5.7 GHz frequency. At this frequency, the offset-reflector configuration exhibits a peak realized gain of 3.25 dBi, with the main beam directed at 12° and a 3-dB HPBW of 75.2° . The corresponding F/B ratio is 0.17 dB, indicating that, unlike the centered configuration, the offset reflector does not produce strong front-to-back radiation discrimination. Instead, its principal benefit is the preservation of the desired resonance while retaining moderate realized gain. At this resonance, the offset-reflector configuration exhibits a radiation efficiency of 94.57%. While the realized gain of the offset reflector configuration is lower than that of the centered reflector configuration, this behavior reflects the trade-off between strong reflector-assisted directivity enhancement and resonance stability. Accordingly, the offset configuration should be interpreted primarily as a resonance-stabilized reflector arrangement rather than as a configuration optimized for maximum directional enhancement.

Thus, the results indicate that maximum gains achieved through a reflector do not necessarily correspond to maximum electromagnetically stable configurations in compact reflector antennas. The offset reflector configuration has established a controlled asymmetric coupling mechanism that allows reduced reflector-induced interaction while at the same time maintaining resonance stability and predictability in the characteristics of the compact single-band resonator.

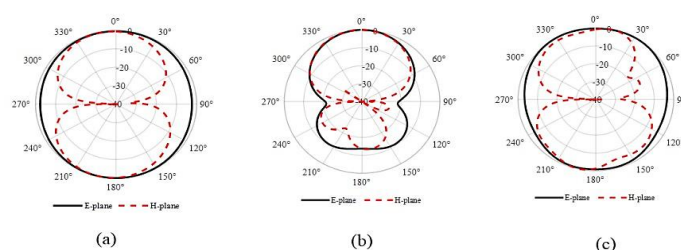


Figure 11. Simulated E-plane and H-plane radiation patterns for the investigated antenna configurations: (a) unloaded antenna, (b) centered reflector, and (c) offset reflector

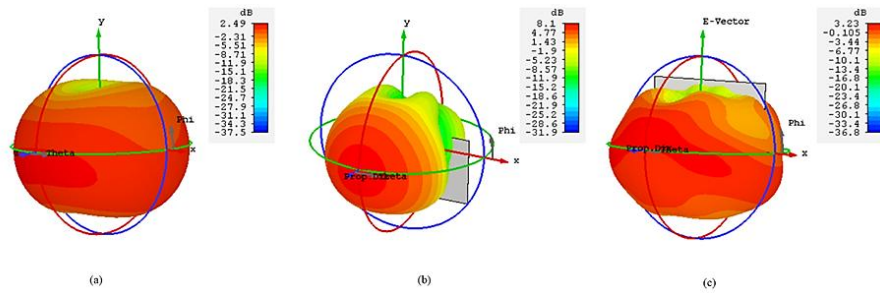


Figure 12. Simulated 3D realized gain patterns for:(a) unloaded reflector at 5.7 GHz, (b) centered reflector at 4.7 GHz, and (c) offset reflector at 5.7 GHz

3.6. Statistical Tolerance Analysis Using Monte Carlo Simulation

A Monte Carlo method for tolerance analysis was conducted to assess how sensitive optimized offset-reflector antenna configurations are to moderate changes in size that would typically occur due to manufacturing conditions. This study specifically attempts to determine how the electromagnetic coupling mechanism and the resultant resonance-stability behaviour of compact antennas are affected by reflector-induced loading. A total of 50 statistically independent realizations were generated around the final optimized dimensions. Gaussian distributions were applied to the upper radiator radius ($\mu=4$ mm, $\sigma=0.05$ mm), lower radiator radius ($\mu=5.5$ mm, $\sigma=0.05$ mm), reflector spacing ($\mu=13.5$ mm, $\sigma=0.15$ mm), and feed width ($\mu=1.5$ mm, $\sigma=0.03$ mm). The reflector-position perturbation was independently sampled from a uniform distribution over $[-2,+2]$ mm around the optimized offset position. The resulting parameter sets were evaluated using full-wave CST simulations. Fifty realizations were selected to provide a representative statistical assessment while maintaining a practical full-wave computational cost.

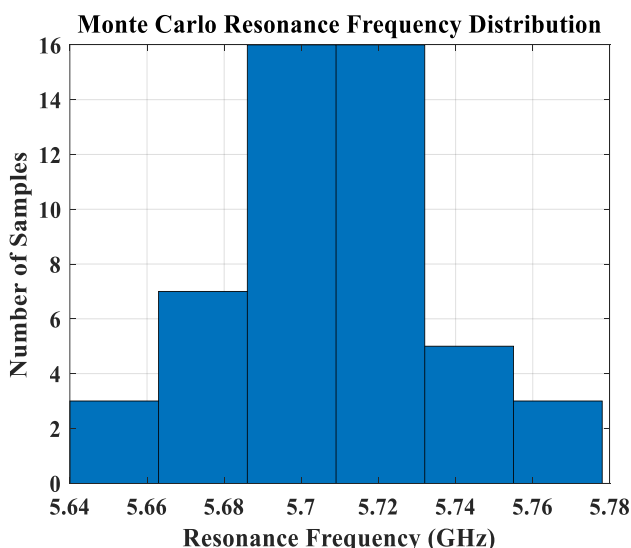


Figure 13. Monte Carlo-based statistical evaluation of resonant frequency and reflection coefficient (S_{11}) variations under dimensional tolerances

The statistical distributions of resonance frequencies that were obtained are outlined in *figure 13*. The distributions show that resonance responses cluster within a narrow operating region around the target frequency, indicating limited resonance dispersion under moderate dimensional variations. The calculated mean resonance frequency is 5.7076 GHz with a standard deviation of 0.0263 GHz; the resonance limits range between 5.6480 GHz and 5.7740 GHz. Moreover, all 50 realizations satisfied the $S_{11} \leq -10$ dB impedance-matching criterion, corresponding to a simulated yield of 100%. Therefore, the statistical results confirm that the optimized offset-reflector configuration preserves stable resonance behavior despite moderate perturbations in both radiator geometry and reflector-positioning parameters.

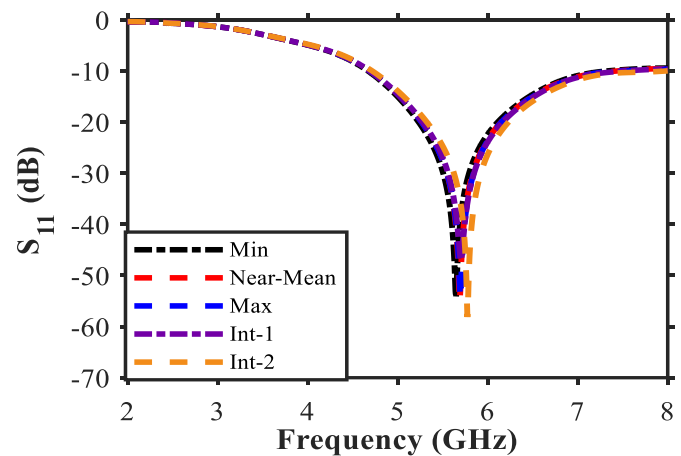


Figure 14. Representative S_{11} responses obtained from the Monte Carlo tolerance analysis of the proposed offset reflector antenna

Representative reflection coefficient responses that were extracted from the Monte Carlo samples are shown in *Figure 14*. The selected curves correspond to the minimum-resonance, maximum-resonance, near-mean resonance, and intermediate operating cases. These representative responses remain within a similar operating region and illustrate the limited resonance dispersion observed across the Monte Carlo analysis. Together with the 100% simulated yield obtained from all 50 realizations, Therefore, the statistical results indicate that the optimized offset-reflector configuration maintains limited resonance variation under the investigated dimensional and reflector-positioning perturbations.

3.7. Experimental Validation of the Reflection Coefficient

Experimental validation was conducted to assess the resonance behavior of the proposed antenna under both unloaded and reflector-loaded conditions. The compact radiator was fabricated according to the optimized geometrical dimensions obtained from the full-wave electromagnetic simulations. Photographs of the fabricated antenna and the experimental measurement arrangements are presented in *figure 15*. The same fabricated antenna prototype was used throughout the measurements to minimize variations associated with fabrication tolerances. For the reflector-loaded measurements, the metallic reflector was positioned according to the centered and proposed offset configurations while maintaining an antenna-to-reflector separation of 13.5 mm.

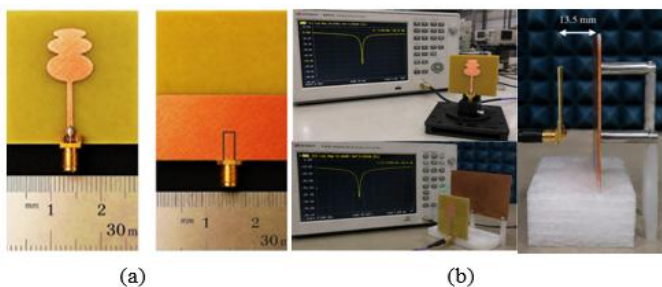


Figure 15. Experimental validation of the fabricated antenna: (a) front and rear views of the fabricated antenna prototype, and (b) experimental S11 measurement setups for the unloaded and reflector-loaded configurations, including a side view showing the 13.5-mm antenna-to-reflector separation

Figure 16 compares the simulated and measured reflection coefficient (S_{11}) responses of the unloaded, centered-reflector, and offset-reflector configurations. Overall, the measured responses show good agreement with the corresponding full-wave simulation results. The centered-reflector configuration exhibits a pronounced downward displacement of the operating resonance relative to the unloaded antenna, demonstrating the strong influence of symmetric reflector loading on the antenna

input response. In contrast, the proposed offset-reflector configuration substantially suppresses this resonance displacement and maintains the measured resonance close to the intended operating frequency. These experimental S11 results therefore support the resonance-detuning behavior predicted by the full-wave simulations and provide experimental evidence for the resonance-stabilization effect achieved through controlled asymmetric reflector placement. Minor discrepancies between the simulated and measured responses may be attributed to fabrication tolerances, SMA connector and soldering effects, uncertainty in the substrate dielectric properties, and practical variations in reflector spacing and alignment.

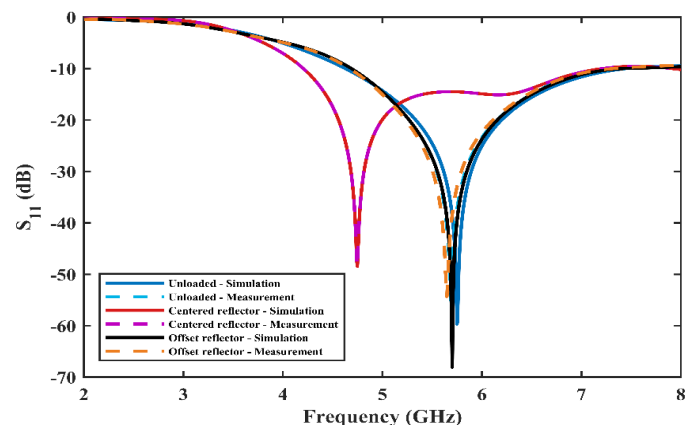


Figure 16. Comparison of the simulated and measured reflection coefficient (S_{11}) responses for the unloaded, centered-reflector, and offset-reflector antenna configurations

3.8. Comparative Discussion

The purpose of this analysis is to further justify the practical relevance and electromagnetic contribution of the proposed reflector-loading strategy through a comparative analysis with recently reported reflector-assisted compact antennas presented in *table 3*, with particular emphasis on the trade-off between realized gain enhancement and resonance stability preservation.

Table 3. Comparative evaluation of recently reported reflector-assisted compact antennas and the proposed offset reflector-loaded antenna configuration.

Ref.	Reflector Type	Freq. (GHz)	Electrical Size	Spacing	Gain/Eff	BW/Validation/Stability
[22]	Metallic MGB	28,38	$1.12\lambda_0 \times 0.75\lambda_0$	9 mm	7.96, 8.20 dBi / $\geq 90\%$	0.8, 5.9 GHz / S&M / Tolerance study
[23]	FSS Reflector	4.3-5.75	$0.224\lambda_0 \times 0.351\lambda_0$	13 mm	9.5-9.67 / 87-96%	NR / S&M / Spacing optimization
[24]	Reflective metasurface	27.14 -40	$4.05\lambda_0 \times 2.10\lambda_0$	0.5 mm	12.3 dBi / $>90\%$	12.86 GHz / S&M / Spacing sensitivity
[25]	FSS reflector (5×5)	3.5	$1.46\lambda_0 \times 1.46\lambda_0$	23.4 mm (0.273 λ_0)	7.93 dBi / 82%	0.50 GHz / S&M / Parametric sensitivity
[26]	Decagonal FSS (4×4)	5.9	$\approx 1.18\lambda_0 \times 1.18\lambda_0$	38.1 mm (0.75 λ_0)	6.42 dBi / $>87.45\%$	0.739 GHz / S&M / Spacing sweep
This work	Offset Metallic Reflector	5.7	$0.57\lambda_0 \times 0.57\lambda_0$	13.5 mm (0.257 λ_0)	3.23/94.57%	2.56 GHz / S / Monte Carlo (50 samples)

The comparative analysis in *table 3* highlights the main contribution of the proposed reflector-loading strategy: achieving directional enhancement while preserving resonance stability. The centered reflector increases the realized gain from 2.4 to 8.1 dBi through strong reflector–radiator coupling; however, it shifts the resonance from 5.7 to 4.7 GHz, corresponding to approximately 17.5% detuning. This demonstrates that maximizing reflector-assisted gain can substantially perturb the operating frequency of a compact resonator.

In contrast, the proposed offset reflector introduces controlled asymmetric coupling that limits excessive image-current interaction and preserves the target resonance near 5.7 GHz. Although the realized gain is reduced to 3.23 dBi, the configuration maintains high radiation efficiency, acceptable impedance characteristics, and directional enhancement without the severe detuning observed under centered loading. The gain reduction therefore represents a deliberate trade-off for improved resonance stability rather than a simple performance loss.

The key contribution is thus not reflector displacement alone, but the use of reflector asymmetry as an electromagnetic coupling-control mechanism. Unlike more complex FSS, metasurface, RIS, or multilayer-based approaches, the proposed configuration provides a simple reflector integration strategy that balances gain enhancement and resonance stability for compact single-band antennas.

4. CONCLUSION

A study was performed on the resonance stability of a compact reflector-loaded antenna employing centered and offset reflector configurations. The results demonstrate that reflector symmetry plays an important role in governing electromagnetic coupling and resonance stability. Full-wave simulations show that the centered reflector increases the realized gain from approximately 2.4 to 8.1 dBi; however, the strong symmetric coupling simultaneously shifts the operating resonance from 5.7 to approximately 4.7 GHz.

To mitigate this detuning, an offset reflector configuration was introduced to establish controlled asymmetric coupling and reduce excessive reflector-induced interaction. The simulated offset configuration preserves operation near the target 5.7 GHz frequency while providing a realized gain of approximately 3.23 dBi, a radiation efficiency of approximately 94%, and VSWR below 2. Experimental S11 measurements of the unloaded, centered-reflector, and offset-reflector configurations confirm the predicted resonance-detuning and resonance-stabilization trends.

Surface-current analysis further demonstrates that the offset reflector modifies the reflector–radiator interaction and reduces excessive reactive loading compared with the centered configuration. Therefore, the lower gain of the offset configuration represents a trade-off between maximum gain enhancement and resonance stability rather than a simple performance degradation. The proposed approach demonstrates

that reflector asymmetry can be used as a controlled electromagnetic coupling mechanism to preserve resonance stability while retaining directional enhancement, without requiring complex metasurface, RIS, multilayer-superstrate, or parasitic-loading structures.

REFERENCES

- [1] da Silva, L.L.; de Lima, L.T.; do Nascimento, D.C. Circularly polarized microstrip antenna on a magneto-dielectric substrate: Design considerations. *IEEE Antennas Wireless Propag. Lett.* 2026. <https://doi.org/10.1109/LAWP.2026.3685593>
- [2] Wang, C.-X.; et al. Modeling, capacity studies, antenna and system designs for 6G/B6G 3D continuous-space radio channels enabled by electromagnetic information theory. *IEEE Commun. Surv. Tutor.* 2025. <https://doi.org/10.1109/COMST.2025.3562896>.
- [3] Chopra, R.; Lakhmani, R. Compact and broadband elliptical microstrip antenna with low cross-polarization. *Proc. IEEE Microwaves Antennas Propag. Conf. (MAPCON)* 2023. <https://doi.org/10.1109/MAPCON58678.2023.10463835>.
- [4] Yadav, M.P.; Singh, R.K.; Ray, K.P. A comparative investigation on the effect of coupling in aperture coupled microstrip antennas. *Prog. Electromagn. Res. C* 2022, 124, 69–79.
- [5] Gustrau, F. *RF and Microwave Engineering: Fundamentals of Wireless Communications*; John Wiley & Sons, 2025.
- [6] Hu, J.; et al. Regulation of forbidden frequency band for noise isolation in PDN using rectangular dielectric EBG units. *Proc. Asia-Pacific Int. Symp. Electromagn. Compat. (APEMC)* 2022. <https://doi.org/10.1109/APEMC53576.2022.9888562>.
- [7] Yang, F.; Rahmat-Samii, Y. Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications. *IEEE Trans. Antennas Propag.* 2003, 51, 2691–2703.
- [8] Costa, F.; Genovesi, S.; Monorchio, A. On the bandwidth of high-impedance frequency selective surfaces. *IEEE Antennas Wireless Propag. Lett.* 2009, 8, 1341–1344.
- [9] Din, I.U.; et al. A novel compact ultra-wideband frequency-selective surface-based antenna for gain enhancement applications. *J. Electromagn. Eng. Sci.* 2023, 23, 159–166. <https://doi.org/10.26866/jees.2023.2.r.159>.
- [10] Soni, D. Design of the U-slotted oval-shaped phase gradient metasurface and antenna for 5G wireless communication. *Results Eng.* 2025, 21, 105880. <https://doi.org/10.1016/j.rineng.2025.105880>.
- [11] Zhu, J.; Liu, J. Design of microstrip antenna integrating 24 GHz and 77 GHz compact high-gain arrays. *Sensors* 2025, 25, 481. <https://doi.org/10.3390/s25020481>.
- [12] Santos, R.A.; et al. Gain enhancement and sidelobe level reduction of microstrip patch antenna under operation of TM50-like mode. *IEEE Open J. Antennas Propag.* 2024, 5, 983–993. <https://doi.org/10.1109/OJAP.2024.3406950>.
- [13] Alibakhshikenari, M.; et al. Metamaterial-inspired antenna array for application in microwave breast imaging systems for tumor detection. *IEEE Access* 2020, 8, 174667–174678. <https://doi.org/10.1109/ACCESS.2020.3025672>.
- [14] Eleftheriades, G.V.; et al. Prospects of Huygens' metasurfaces for antenna applications. *Engineering* 2022, 11, 21–26. <https://doi.org/10.1016/j.eng.2021.05.011>.
- [15] Levin, B. *Antenna Engineering: Theory and Problems*; CRC Press, 2017.
- [16] Balanis, C.A. *Antenna Theory: Analysis and Design*, 4th ed.; Wiley: Hoboken, NJ, USA, 2016.
- [17] Douhi, S.; et al. Design of a flexible rectangular antenna array with high gain for RF energy harvesting and wearable devices. *J. Nano-Electron. Phys.* 2023, 15. [https://doi.org/10.21272/jnep.15\(3\).03010](https://doi.org/10.21272/jnep.15(3).03010).
- [18] Elwi, T.A.; et al. On the performance of a photonic reconfigurable electromagnetic band gap antenna array for 5G applications. *IEEE Access* 2024, 12, 60849–60862. <https://doi.org/10.1109/ACCESS.2024.3392368>

- [19] Ahmed, O.F.; Thaher, R.H.; Ahmed, S.R. Design and fabrication of broadband microstrip antenna on various substrates. AIP Conf. Proc. 2023, 2834 . <https://doi.org/10.1063/5.0163187>
- [20] Huy  n, M. Design of a four-element array antenna for 5G cellular wireless networks. Eng. Technol. Appl. Sci. Res. 2022.
- [21] Hossain, M. B., M. R. I. Faruque, and M. T. Islam, “Double elliptical resonator-based quadruple band metamaterial absorber for EMI shielding applications in microwave regime,” Alexandria Engineering Journal, Vol. 71, pp. 391-402, 2023, <https://doi.org/10.1016/j.aej.2023.01.035>
- [22] Mohammed, D.Z.; Al-Gburi, A.J.A. Compact, gain-enhanced 5G mmWave antenna with metallic ground-backed reflector for high-speed railway communication systems. High-Speed Railway 2025. <https://doi.org/10.1016/j.hspr.2025.08.004>.
- [23] Kareem, Q.H.; Al-Obaidi, M.K.; Abdullah, S.N. Optimal reflector surface of compact quasi-omnidirectional tuning antenna for gain enhancement at sub-6 GHz applications. AEU - Int. J. Electron. Commun. 2025, 200, 155924. <https://doi.org/10.1016/j.aeue.2025.155924>
- [24] Kiani, S.H.; et al. Low-profile metasurface-backed wideband antenna array for mm-wave applications. Sci. Rep. 2026. <https://doi.org/10.1038/s41598-026-37435-9>
- [25] Palanisamy, S., Nallusamy, S., Thangavelsamy, N., Guizani, S., Hamam, H. (2025). High-performance Sub-6GHz 5G antenna with frequency selective surface integration: Design, optimization and experimental validation. Traitement du Signal, Vol. 42, No. 4, pp. 1823-1839. <https://doi.org/10.18280/ts.420401>
- [26] Troudi, I.; et al. Integration of frequency selective surfaces with MIMO antennas for enhanced performance in IoT and V2V communication systems. Sci. Rep. 2025, 15, 35545. <https://doi.org/10.1038/s41598-025-19483-9>



  2026 by Narmin H.AL-Zahawi, Haveen Yaseen Hussein AL-Zahawi, Saja Mazin Sami, and Zainab S. Husamuldeen. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).